Experimental Evaluation of a Basic Staged Combustion Configuration

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ABSTRACT

The effect of a secondary “weak” jet on a “strong” jet’s flow field is of great importance for the evaluation of many staged combustion schemes. The present work is part of ongoing research on turbulent mixing characteristics of the interaction of a weak and a strong jet inside a confining area, with experimental and numerical tools. Preliminary experimental results, obtained with laser Doppler anemometry, will be presented. Measurements of mean and turbulent velocity statistics of a single turbulent axisymmetric jet are presented for reference. At a distance of thirty strong jet’s diameters, mean and rms velocity profiles of jets’ merging are presented for isothermal conditions. In this test case momentum flux ratio of jets is rather high. Two local maximums corresponding to the central region of each jet are identified. A slight displacement of weak jet’s maximum and a small increase of turbulent components at the edges of jets indicate early stages of mixing.

INTRODUCTION

Strong and weak jets are widely used in the modern design of industrial burners since wise air and fuel mixing can result to a “clean” and efficient combustion configuration. Although this type of burners is already used in industrial applications, the analytical description of the turbulent mixing characteristics is still an open field for scientific research. In this frame, the laboratory of Applied Thermodynamics has focused on the development of a basic staged combustion configuration, including the study of the interaction of a strong and a weak jet, issuing in parallel inside a semi-confining test area.

![Fig. 1 Staged Combustion: 0-1 Low Temperature, Fuel Rich Mixture, 1-2’ Quenching, 2’-2 Fuel Lean Mixture, 1-3 real stage (from ref [1]).](image)

The strategic objective of staged combustion scheme is to take advantage of the low NOx production associated with lean or rich combustion that is combustion far from stoichiometry. The basic concept is shown in figure 1. On the first stage combustion of a rich
in fuel mixture takes place. The second stage includes a quick and homogeneous mixing and quenching and at the last stage combustion is completed in a lean mixture. The challenge in real combustors is to achieve a realistic 1-3 path to optimise the mixing and quenching process, so that the effective path comes as close as possible to the ideal 1-2’ path. The efficiency of the technique is based on the quick mixing of rich products and air and the removal of substantial amounts of heat, in order to avoid additional emissions production [1].

In gas turbine combustion the efficient mixing and quenching is achieved through proper design of the geometry [2,3]. However in most industrial applications, as for example in glass furnaces, the optimisation of the important stage of combustion is related to the turbulent characteristics of jets confluence. In the case of inclined at the same angle and equal

![Fig. 2 Jets Pairing, from ref [4]](image)

in strength jets’ merging, which is usually studied, the flow field is separated in three main regions [5]. The regions include the pre-mixing zone, where no direct mixing between jets takes place but both the jets entrain air from the surroundings, the mixing or confluence zone, where a strong interaction between jets dominates the flow field and the post mixing or dilution zone, where the resulting structure, similar to the far field of a single turbulent jet, contains fully mixed gases and continues to mix with the ambient air.

The flow field (figure 2) is affected by geometry parameters and exit conditions. An effort for minimizing the number of parameters on the aerodynamic modeling of jets pairing [6] has shown that the crucial parameters are the distance and the angle between the port axes and the ratio of momentum fluxes of jets that could be adjusted to approach the typical values used in combustion systems. Computational predictions from previous work [7] reveal the strong effect of the inclination angle and the influence of the momentum flux ratio on the location of the critical point of confluence.

In this study, laser Doppler anemometry measurements of mean velocities and turbulent statistics of the single strong jet at 20 and 30 diameters downstream are presented. This set of measurements constitutes a basis for the evaluation of the measuring technique, but also a point of reference on the effect of the secondary weak jet. Lda measurements of the two jets are also presented at 30 strong jet’s diameters. Due to high momentum flux ratio jets are acting almost independently in this region but a slight displacement of weak jet’s maximum and a small increase of turbulent components at the edges of jets indicate early stages of mixing.
TABLE 1. Parameters of the LDA optical system

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<th>Transmitting optics</th>
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<tr>
<td>Wavelength of the laser</td>
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<td>Diameter of laser beam</td>
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<td>Focal length of transmitting lens</td>
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<td>Beam separation</td>
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<td>Fringe number</td>
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<td>Focal length of receiving lens</td>
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EXPERIMENTAL APPARATUS

Figure 3 shows a schematic of the experimental apparatus. Both the jets were issuing from 50 cm length pipes, in parallel inside the confining area with dimensions of 900x900x1000 mm³. Diameters for strong and weak jet were 6 and 4 mm respectively and the distance between port axes was 7 cm. The roof was open and jets’ exits were positioned 10 cm above the lower surface of the test section. The effect of the confinement is under experimental investigation, although previous predictions [4] indicate that momentum is largely conserved.

Both the jets were supplied by compressed air. Seeding particles were illuminated by a 632.8 nm wavelength He-Ne laser. A Dantec Burst Spectrum Analyzer (BSA) was used to measure the mean and turbulent velocity field. The scattering angle was 10 degrees off axis from the forward scattering direction to avoid depth of focus effects on the control volume. The dimensions and the characteristics of the optical system are shown in table 1. Sampling was depending on seeding presence and signal processor logic. 15000 validated samples were recorded on average for each measurement point. Low data rate problems, especially in measurements of the interacting jets, forced to accept only 5000 samples at some points. A 3-D traversing mechanism was available for positioning both transmitting and receiving optics. A commercial atomizer seeded only the strong jet with water and glycerin fog.

![Fig. 3 Schematic diagram showing the main components of the experimental apparatus](image-url)
RESULTS

Single Jet

Preliminary measurements on the turbulent axisymmetric jet are presented in figures 4-8. The “strong” jet has an initial Reynolds number of 15000. Figure 4 shows the exit velocity profile measured at a distance of 0.5 diameters downstream. The profile is in agreement with previous reports on long pipe jets [8] and also with the analytical relation proposed for fully developed turbulent flow in pipes.

Figure 5 shows the mean and turbulent velocity components respectively, at a distance of 20 diameters downstream from the jet exit. Measurements of mean velocity coincide with typical Gaussian curves that are commonly used to describe analytical relations of the velocity profiles [9]. Measurements at the edge of the jet were unattainable as the seeding density was quite low. Turbulence measurements are shown to exaggerate typical values on the jets axis. Figure 6 shows the mean and turbulent quantities 30 diameters downstream. The rms values on the central axis are lower at this distance.
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Fig 6. Mean and turbulent radial profiles 30 diameters downstream:
(a) $\text{Gaussian}$, (b) $\text{polynomial}$

Fig. 7 (a) Skewness and (b) Flatness factors at 30 diameters downstream from jet exit:
$\text{lda measurements}$, $\text{polynomial}$

Fig. 8 Probability density functions: (a) 20 diameters, (b) 30 diameters from jet exit

Probability density function distributions of velocity for the axisymmetric jet 30 diameters from jet exit are shown in figure 8. Near to the axis distributions are wider and at the edge peaks achieve higher values. As also skewness and flatness factors indicate
(figure 7), the pdfs are almost normal near the central region of the jet, deviating from normal with positive skewness and higher flatness towards the jet’s edge.

**Jets Interaction**

![Figure 9](image)

*Fig. 9  (a) Mean and (b) turbulent radial profiles of velocity 30 "strong" jet's diameters downstream*

The mean and turbulent velocity profiles for jets interaction at a distance of 30 strong jets diameters are presented in figure 9. The “weak” jet has an initial Reynolds number 3200 and the momentum flux ratio is about 0.5. At this distance from port axis two local maximums corresponding to the central region of each jet are identified in the mean profile. A slight displacement of weak jet’s maximum and a small increase of turbulent components at the edges of jets indicate early stages of mixing.

**AKNOWLEDGMENTS**

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**LITERATURE**